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MEASUREMENT OF GAS DENSITY IN A SUPERSONIC RAREFIED FLOW
BY MEANS OF GLOW-DISCHARGE LUMINESCENCE

V. N. Kalugin

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MEASUREMENT OF GAS DENSITY IN A SUPERSONIC RAREFIED FLOW
BY MEANS OF GLOW-DISCHARGE LUMINESCENCE

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ABSTRACT. The relationship was found between gas density in supersonic rarefied flow and negative luminescence in a glow-discharge. Some results are given of density measurement in a free stream and in a model. It is shown that density measurement of negative luminescence of a glow-discharge is effective in static pressure range of $5 \cdot 10^{-2}$ to $5 \cdot 10^{-4}$ mm of mercury.

Thanks to the simplicity of the apparatus used, glow-discharge radiation /106* is a widely used method for observing rarefied streams in low-density wind tunnels (for example, see [1,2]). However, because of the complexity of processes leading to the development of luminescence, the ratio between intensity of luminescence and gas density has not been established. Therefore, this method allows only a coarse estimate of density distribution.

In [3] is a description of visual representation of a stream using the negative luminescence of a glow-discharge, in which a supersonic jet is used as the cathode element. It was found that luminescence is generated by electrons with an energy corresponding to the drop in cathode potential. Because of the dispersion of electrons upon collision with molecules, the concentration of electrons and radiation intensity decreases as the distance from the jet increases. Below, based on the results of work [3] are the ratios obtained, in which gas density distribution in a stream is calculated from the distribution of radiation intensity. As in [3], the test gas used was nitrogen or air, but other gases may be used as well for this method.

1. In the case of hydrogen or air medium and at sufficiently low pressure, the negative radiation spectrum is a band of the first negative hydrogen system. Intensity of the other spectral systems in the visible region can be disregarded. It is known that intensity of energy band $i(\nu', \nu'')$ corresponding to luminescence transition from energy level ν' of the higher electron

*Numbers in the margin indicate pagination in the foreign text.

state to energy level v'' of the lower electron state, is written in the form

$$i(v', v'') = g(v') a(v', v'') h\nu(v', v'') \quad (1)$$

Here $a(v', v'')$ is the probability of transition, h is Plank's constant, $\nu(v', v'')$ is radiation frequency. The condition of excitation is considered in the product $g(v')$, which in the case of electron excitation is expressed in the form

$$g(v') = \sum_{v_1''} N(v_1'') n(v', v_1'')^2 \int_E R_e^2(r_{v', v_1''}, E) f(E) dE \quad (2)$$

Here $N(v_1'')$ is concentration of molecules at energy level v_1'' at the lower electron state, from which entrance to level v' at the upper electron state is realized; n is electron concentration; (v', v'') is the overlap integral; $R_e(r_{v', v_1''}, E)$ is the electron moment of transition; $r_{v', v_1''}$ is the r -centrode; $f(E)dE$ is the portion of electrons with energies between E and $E + dE$.

At medium high gas temperature ($\leq 1000^\circ\text{K}$) one can say that all molecules are initially at the zero energy level of the basic electron state. We will also assume that for the first few energy levels for relatively high electron energies, the ratio of R_e to internuclear distance is extremely small [4,5]. Then

$$g(v') = N(0) n(v', 0)^2 \int_E R_e^2(E) f(E) dE \quad (3)$$

Radiation intensity I of the negative nitrogen system equals the sum of the individual intensities of the bands, i.e.,

$$I = \sum_{v', v''} i(v', v'') = A(v', v'') N(0) n \int_E R_e^2(E) f(E) dE \quad (4)$$

$$A(v', v'') = \sum_{v', v''} a(v', v'') h\nu(v', v'') (v', 0)^2$$

Thus radiation intensity is proportional to the concentration of molecules (gas density) and to electron concentration. However, determination by the absolute intensity of molecular concentration has a number of difficulties

associated with it. Therefore we will examine another possibility.

Let axis z be oriented along the axis of the jet. As sufficiently low /107
pressure the energy change of electrons along axis z within the limits of the observable region can be disregarded [3,6]. Then the relative change in intensity of radiation during the movement from point z to point $z+dz$ is

$$\frac{dI(z)}{I(z)} = \left[\frac{1}{N(z)} \frac{dN(z)}{dz} + \frac{1}{n(z)} \frac{dn(z)}{dz} \right] dz \quad (5)$$

Or, introducing gas density $\rho(z)$ in place of molecular concentration $N(z)$, we obtain

$$\frac{dI(z)}{I(z)} = \left[\frac{1}{\rho(z)} \frac{d\rho(z)}{dz} + \frac{1}{n(z)} \frac{dn(z)}{dz} \right] dz \quad (6)$$

Electron concentration in a beam decreases with distance from the jet, and the gradient of electron concentration along axis z is defined as

$$(z)u(z) \text{ chl} = - \frac{zp}{(z)up} \quad (7)$$

where μ is the coefficient of weakening of the electron beam [3]. Calculating (7), we obtain

$$\frac{d\mu(z)}{dz} - \frac{d \ln I(z)}{dz} \rho(z) = \mu \rho^2(z) \quad (8)$$

$$\rho(z) = \rho(z_0) \frac{I(z)}{I(z_0)} \left[1 - \mu \rho(z_0) \int_{z_0}^z \frac{I(z)}{I(z_0)} dz \right]^{-1} \quad (9)$$

Initial point z_0 is easily selected from the following considerations. Ordinarily in a supersonic free stream one can find a fairly small Δz , along the length of which the change in density is negligibly small. Then for this component $d\rho/dz \approx 0$ and equation (8) can be written in the form

$$\frac{d \ln I(z)}{dz} = -\mu \rho \quad (10)$$

Since ρ in this case is independent of z , then the plot of $I(z) = f(z)$ represents a straight line, from whose slope one can determine the value of density ρ . To find the density value for each point z using formula (9) it is logical to take the values of quantities z_0 , $I(z_0)$ and $\rho(z_0)$ corresponding to the final component of the linear function (10), i.e., at the point where the density gradient becomes other than zero, and the plot of $\ln I(z) = f(z)$ ceases to be linear.

To determine the density at any point in the stream, one must substitute into the formulas obtained the values of radiation intensity and the preceding points along axis z . In the case of a smooth flow it is possible to use the integral values of radiation intensity observed along the line. For more complex spacial distribution of gas density and radiation intensity, calculation of density is more involved. In particular, the familiar method of calculating symmetrical axis non-uniformity can be used to determine the density fields if there is axial symmetry of the distribution of density in the supersonic stream and in the model.

For photographic recording of radiation and work on the linear portion of the characteristic intensity curves, radiation intensity can be expressed by darkness of the emulsion $D(z)$. Then

$$I(z)/I(z_0) = 10^{[D(z)-D(z_0)]/\gamma} \quad (11)$$

where γ is the coefficient of the emulsion contrast. By this means, in sectors where density is a function of z ,

$$\rho(z) = \rho(z_0) 10^{[D(z)-D(z_0)]/\gamma} \left[1 - \mu \rho(z_0) \int_{z_0}^z 10^{[D(z)-D(z_0)]/\gamma} dz \right]^{-1} \quad (12)$$

For the portion with constant density we obtain

$$\rho = -\frac{2.3}{\mu \gamma} \frac{dD(z)}{dz} = -\frac{2.3}{\mu \gamma} \frac{D(z_2) - D(z_1)}{z_2 - z_1} \quad (13)$$

Points z_2 and z_1 are in the extremes of the region where $d\rho/dz = 0$ and the ratio of D to z is linear.

The value of the coefficient μ can be found by doing preliminary calibration tests with a known gas density. By studying the passing flow of molecules, density is usually determined in the form of a relative value such as the form ρ_∞/ρ (ρ is density of the entering stream). In this case there is no need for the values of coefficient μ in the initial measurement; $\mu\rho_\infty$ is calculated from the inclination of the linear part of the D/z graph and substituted in (12).

2. Density measurement was made in a low-pressure wind tunnel. The experimental set-up is described in [3]. The test gas was dry air. Preliminary calibration tests were conducted initially to determine the coefficient μ . The value of μ depends on the cathode potential decrease, which cannot be determined in each specific experiment. Therefore it is more expedient and convenient to obtain the ratio from decay of potential u_- across the discharge gap. Figure 1 illustrates such an experimentally determined ratio. Measure-

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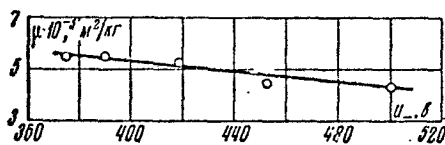


Figure 1.

ment error was about 5%. One can see that μ decreases as the potential increases. This phenomenon is in agreement with the generally accepted concept of the dependence of effective cross section of electron-atom (molecule) collision on its energy.

Gas density measurement in the supersonic stream beyond the (compression) change in the model was made in conditions of not too great a rarefaction, where it was still possible to compare the results of parameter value changes, which were calculated by means of continuous correlations. As a model, a streamlined round cylinder was used transversely. The length of the cylinder was made long enough that flow parameters in the model within the limits of the length of the radiation zone along the axis of observation were not distributed by boundary effects, and flow could be considered plane. The conditions of supersonic flow were as follows: Mach No. $M_\infty = 5$, static pressure $p_\infty = 5.5 \cdot 10^{-3}$ mm of mercury, deceleration was at room temperature. If the cylinder radius is taken as typical, then the Reynold's number is $R_\infty = 280$ and Knudsen's No. is $K = 0.027$.

Figure 2 shows a photograph of streamline flow of the model. The negative was exposed in the direction from the jet to the model along the axis of the jet. A micrograph of radiation (curve 1) and density distribution (curve 2) along the deceleration line of the model is shown in Figure 3.



Figure 2.

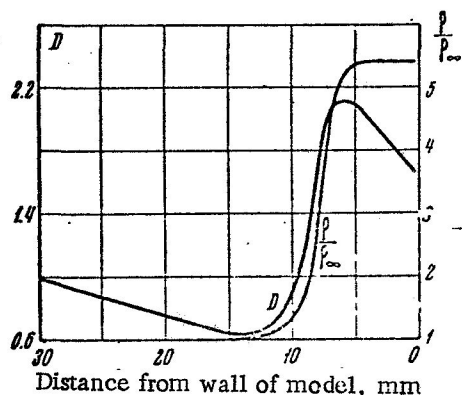


Figure 3.

Note that the compression change is rather strongly broadened; this is characteristic for rarefied gas flow. The correlation of gas densities within the limits of measurement error which was reached beyond the change in the model corresponds to the calculated value from the Rankine-Pugoniot relations, which equals 5 for $M_\infty = 5$. Thus the results of the experimental studies made agree with the calculated values, which supports the validity of the premises made and the suitability of the suggested method for experimental determination of the streamline spectrum of the model by rarefied flow.

Construction of density fields provides the most complete representation of the gas density distribution in a supersonic stream. Here it is important whether the density field is calculated according to the streamline profile obtained as a result of one measurement or the study is made by the

"point-for-point" method. In the latter case one must keep the wind tunnel parameters constant as well as those of the measuring apparatus over an extended time period, which is not always accomplished. An important feature of the described method is the capability of photographing the entire picture of the stream and then calculating the density at any point. The lines of even density at the crossways air-stream cylinder obtained by this means for $M_\infty = 5$, $R_\infty = 57$, $K = 0.13$, are shown in Figure 4; ξ is the distance from the forward

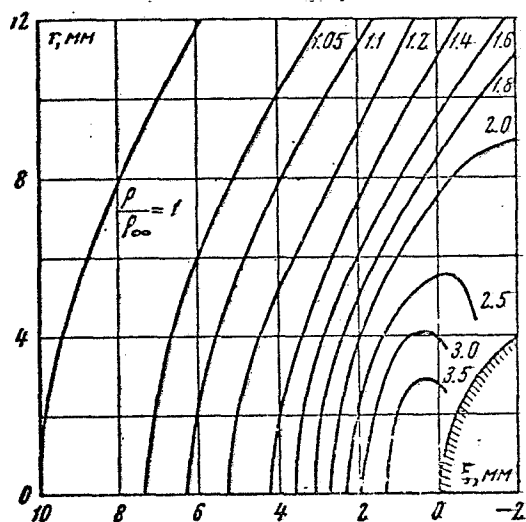


Figure 4.

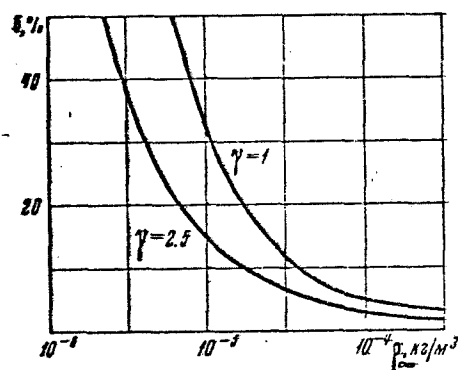


Figure 5.

wall of the cylinder along the brake line, r is the distance from the plane lying on the axis of the cylinder and the brake line. One can calculate the field and other parameters under specific conditions according to the density distribution.

3. Measurement error relative to density value $\delta = \frac{\Delta[\rho(z)/\rho_\infty]}{\rho(z)/\rho_\infty}$ is determined basically by the degree of rarefaction and photo emulsion contrast coefficient γ (Figure 5). Maximum possible measurement error for photographing on film with $\gamma = 2.5$ becomes large (about 25%) for $\rho = 5 \cdot 10^{-6}$ mm of mercury. This value, to which corresponds static pressure, or about $5 \cdot 10^{-4}$ mm of mercury, can apparently be taken tentatively as the lower limit when using the described method. The upper limit is determined from the condition

$$\int_{z'}^{z''} \mu \rho dz \approx \mu \langle \rho \rangle (z'' - z') < 1,$$

and depends on experimental conditions. We note that in the case in question

density measurement at the cylinder, $\mu_{\langle \rho \rangle}(z''-z')$, is a value near unity, but the deviation of the measured value from the calculated one still does not exceed measurement error.

As the extreme pressure limit one can tentatively indicate a value of $5 \cdot 10^{-2}$ mm of mercury. Thus the method of measuring density in rarefied flow by relative intensity of negative glow-discharge luminescence can be used in a pressure range from $5 \cdot 10^{-2}$ to $5 \cdot 10^{-4}$ mm of mercury.

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